Chapter 8
The Integration of Micro-CHP and Biofuels for Decentralized CHP Applications

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Abstract Renewable micro-CHP systems are a combination of micro-CHP technology and renewable energy technology, such as biomass gasification systems or solar concentrators. The integration of renewable energy sources with micro-CHP allows for the development of sustainable energy systems with the potential for high market penetration; a cost-effective and reliable heat and electricity supply; and a highly beneficial environmental and economical impact on a pan-European scale. The purpose of this chapter is to present results from the European co-ordination action project MICROCHEAP that intended to bring together industrial specialists and research experts to focus entirely on renewable micro-CHP technology, co-ordinate and steer research in this field, and highlight the most promising technologies with the highest potential for market penetration in existing and future market conditions. The chapter discusses the state of the art technological options in the field of renewable micro-CHP with biofuels with regards to technology, cost, and environmental impacts and presents a market survey concerning the possibility of future penetration of the technology in Europe. The results will provide a coherent overview of the basic technological options for renewable micro-CHP with biofuels and will provide an insight to the market trends within Europe and projected future market scenarios, taking into account cost estimations for various micro-CHP technologies, feedstocks, and electricity and fuel prices in Europe.

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8.1 Introduction

Conventional power generation consists of large central plants connected to a grid supplying power to the customer. While such systems offer centralization they suffer from significant thermal losses as well as line transmission losses. Critical is the distribution grid that must be maintained and expanded to meet growth. To expand the grid realistically in today's environment is difficult. Not only from a practical perspective but unattainable in most metropolitan areas simply due to density and the NIMBY principal (Not In My Back Yard). The end result is the customer pays for these inefficiencies not only in cost of power but also in power outages, power sags and surges, and unstable frequency, *etc.*

Combined heat and power (CHP) systems (also known as cogeneration) generate electricity and thermal energy in a single, integrated system. In a traditional power plant that delivers electricity to consumers, about 30% of the heat content of the primary heat energy source reaches the consumer, although the efficiency can be 20% for very old plants and 45% for newer gas plants. In contrast, a CHP system converts 15–42% of the primary heat to electricity, and most of the remaining heat is captured for hot water or space heating. In total, as much as 90% of the heat from the primary energy source goes to useful purposes when heat production does not exceed the demand. Cogeneration works in parallel with the utilities grid reducing the strain. In critical power quality needs it can act as a filter to bring true high quality power that meets the client's needs. In some cases (depending on local and state regulation) a cogeneration plant can be designed to generate excess power for sale onto the grid creating an additional revenue source for the client.

CHP systems have benefited the industrial sector since the energy crisis of the 1970s. For three decades, these larger CHP systems were more economically justifiable than micro-CHP, due to the economy of scale. After the year 2000, micro-CHP has become cost effective in many markets around the world, due to rising energy costs. The development of micro-CHP systems has also been facilitated by recent technological advances in small heat engines. This includes improved performance and/or cost-effectiveness of {Stirling, steam, diesel, Otto} engines and gas turbines. The main difference of micro-CHP systems from their larger-scale kin is in the operating parameter-driven operation. In many cases industrial CHP systems primarily generate electricity and heat is a useful by-product. In contrast, micro-CHP systems, which operate in homes or small commercial buildings, are driven by heat-demand, delivering electricity as the by-product. Because of this operating model and because of the fluctuating electrical demand of the structures in which they would tend to operate, homes and small commercial buildings, micro-CHP systems will often generate more electricity than is instantly being demanded.

Renewable micro-CHP systems, on the other hand, are a combination of micro-CHP technology and renewable energy technology, such as biomass gasification systems or solar concentrators. The integration of renewable energy sources with

micro-CHP allows for the development of sustainable energy systems with the potential for high market penetration. These technologies potentially have much to offer in helping us to achieve our objectives of tackling climate change, ensuring cost-effective and reliable heat and electricity supply and tackling fuel poverty. As well as providing low carbon energy to homes and small commercial buildings, micro-generation can provide the same service to community buildings, such as leisure centers and schools. In such premises, not only does the micro-generation installation help to reduce carbon emissions; it can also help to educate and inform communities about energy and, hopefully, persuade people to reduce their own carbon footprint.

The current work presents results from the European co-ordination action project MICROCHEAP that intended to bring together industrial specialists and research experts to focus entirely on renewable micro-CHP technology, co-ordinate and steer research in this field, and highlight the most promising technologies with the highest potential for market penetration in existing and future market conditions. The chapter discusses the state of the art technological options in the field of renewable micro-CHP with biofuels with regards to technology, cost, and environmental impacts, and presents a market survey concerning the possibility of future penetration of the technology in Europe.

8.2 State of the Art of Micro-CHP with Biofuels

Directive 2004/8/EC of 11 February 2004 "on the promotion of co-generation based on a useful heat demand in the internal energy market" provides the following definition of micro-CHP: 'micro-cogeneration unit' shall mean a cogeneration unit with a maximum capacity below 50 kWe. The suite of technologies caught by this definition includes solar (photovoltaics – PV – to provide electricity and thermal to provide hot water), micro-wind (including the new rooftop mounted turbines), micro-hydro, heat pumps, biomass, micro combined heat and power (micro CHP), and small-scale fuel cells [1]. The current work will focus on micro-CHP technologies that can be used in combination with biofuels, and will focus on three main systems using the most commercially available to date technologies: micro-turbines, Stirling engines, and fuel cells.

8.2.1 Micro-Turbines for Micro-CHP

The operating theory of the micro-turbine is similar to the gas turbine, except that most designs incorporate a recuperator to recover part of the exhaust heat for pre-heating the combustion air and increase the electric efficiency. Air is drawn through a compressor section, mixed with fuel, and ignited to power the turbine section and the generator. Hot exhaust gas from the turbine section is available for

Table 8.1 Current manufacturers of micro-turbines (less than 200 kWe)

Manufacturer	Range of models
Capstone Turbine Corporation	30, 60 kWe (next 200 kWe)
Elliot Energy Systems Inc.	80 kWe
Turbec AB	100 kWe
Bowman Power Ltd.	50, 80 kWe
Ingersoll–Rand Energy Systems	70 kWe (next 250 kWe)

CHP applications (hot water heating or low pressure steam applications). The high frequency power that is generated is converted to a grid compatible 50 Hz through power conditioning electronics. Their compact and lightweight design makes micro-turbines an attractive option for many light commercial/industrial applications.

Most manufacturers are pursuing a single-shaft design in the 25–250 kW range, where the compressor, turbine, and permanent-magnet generator are mounted on a single shaft supported on lubrication-free air bearings. These turbines operate at speeds of up to 120,000 rpm and can be operated on a variety of fuels, such as natural gas, gasoline, diesel, alcohol, biofuels, *etc.* With recuperation, efficiency is currently in the 25–30% LHV range, or even higher for new designs. Table 8.1 shows a list of the current manufacturers of micro-turbines below 200 kWe [2], while Table 8.2 presents the general specifications of market micro-turbine co-generation systems [3].

Installed prices of $800–1200/kW for CHP applications is estimated when micro-turbines are mass produced, while availability is similar to other competing distributed resource technologies, *i.e.*, in the 90–95% range. Micro-turbines have substantially fewer moving parts than engines. The single shaft design with air bearings will not require lubricating oil or water, so maintenance costs should be below conventional gas turbines. Micro-turbines that use lubricating oil should not require frequent oil changes since the oil is isolated from combustion products. Only an annual scheduled maintenance interval is planned for micro-turbines.

Table 8.2 General specifications of some market micro-turbine CHP systems [3]

	Capstone micro-turbine					Elliot/ Bowman	Turbec
	NG/ gaseous propane	Diesel or kerosene	Biogas (landfill or digester gas)	NG		NG, propane, LPG, and butane	NG
Electrical capacity (kW_{el})	30	30	30	28	60	80	105
Electrical efficiency (%) LHV	26	25	26	25	28	28	30
Overall efficiency (%) LHV	91	90	91	91	89	75	78
Thermal output (kW)	85	85	85	85	150	136	167

Table 8.3 Micro-turbine emission characteristics [3]

	Capstone model 330	Ingersoll–Rand Energy Systems 70LM (two shaft)	Turbec T100
Nominal capacity, kW_{el}	30	70	100
Electrical efficiency (%) HHV	23	25	27
NOx, ppmv	9	9	15
CO, ppmv	40	9	15
THC, ppmv	< 9	< 9	< 10
CO_2, lb/MWh	1928	1774	1706
Carbon, lb/MWh	526	484	465

Maintenance costs are being estimated at 0.006–0.01$/kW. Micro-turbines also promise lower noise levels and can be located adjacent to occupied areas [4–6].

Micro-turbines have the potential for producing low emissions. They are designed to achieve low emissions at full load; however, emissions are higher when operating under reduced load. Today's micro-turbines have a greater efficiency and lower emissions of greenhouse gases than internal combustion engines [7]. Low emission combustion systems are being demonstrated that provide emissions performance comparable to larger CHP turbines. The main pollutants from the use of micro-turbine systems are NO_x, CO, CO_2, and unburnt hydrocarbons, and negligible amount of SO_2. NO_x emissions are targeted below 9 ppm using lean pre-mix technology without any post combustion treatment. Emission characteristics of micro-turbine systems based on manufacturers' guaranteed levels are given in Table 8.3.

8.2.2 Stirling Engines for Micro-CHP

Stirling engines are closed cycle engines operating on the Stirling cycle, characterized by an external heat supply. An external heat supply allows the use of any heat source operating at a sufficient temperature level. The Stirling engine operates by continuous heating and cooling of a fully enclosed working gas, usually helium, air/nitrogen or hydrogen. The alternate compression and expanding of a fixed amount of high pressure gas is transformed into a rotating movement to which the electric generators are connected. The continuous external combustion process of the Stirling engine provides good combustion control and low exhaust emission levels. Within the closed Stirling cycle, pressure variations of the working gas follow an almost sinusoidal curve, which is one of the basic reasons for the low noise and vibration level of a Stirling engine. Another reason for the low noise is that there is no connection between the working gas and the outside atmosphere as opposed to the exhaust pipe of an IC engine.

The Stirling engine was first patented in 1816 by Robert Stirling as an application of the regenerator he had invented. Throughout the nineteenth century, several working models were built and some were operated successfully for a while, but eventually more effective and powerful steam and internal combustion engines replaced the Stirling engines. The development of the modern high speed Stirling engine with a pressurized gas cycle started in the 1930s. The Philips electric company did pioneering work and although Philips abandoned Stirling development in the 1970s, most Stirling engines that are on the market today use solutions that were originally developed at Philips.

Two main families represent modern Stirling engines: kinematic and free piston Stirling engines. Kinematic Stirling engines are the largest group of Stirling engines. In these engines, the reciprocating movement of the power piston is transferred to a rotating shaft by mechanical means. The engines can be used to drive an electric generator. Depending on the geometric arrangement of the pistons (and displacers), different variants are the alpha, beta, or gamma engines. Depending on the interconnection of multiple cylinders, these engines can operate with single or double acting pistons. Kinematic engines have been demonstrated in the power range 0.1–500 kW. In free piston engines the reciprocating movement of the power piston is used to drive a linear electric generator. These engines are comparatively simple in mechanical terms and require little maintenance. Free piston engines have been demonstrated in the power range 0.05–3 kW [8].

The main feature that distinguishes modern Stirling engines from competing technologies such as internal combustion engines and fuel cells is the flexibility of the heat source. Stirling engines can be heated by concentrated sunlight, waste heat, and, depending on an appropriate burner design, a host of different fuel types. Stirling engines are therefore well placed for applications involving:

- concentrated sunlight: solar dish Stirling engines;
- combustion of biomass: biogas or oil fired Stirling engines.

Because Stirling engines are comparatively quiet and the external burners can operate with very low emission levels Stirling engines are also suitable for use in the built environment. As a result there has been an extensive effort in the past decade to develop Stirling engines custom made for micro-cogeneration systems. The Stirling engine technology is still not quite developed and represent an emerging technology although some applications already exist. They are commercially available as 55-kW units and are projected to be available in 150- to 300-kW sizes. They are also manufactured for much smaller powers of 1 kWe (or less) to a few kWe. The units generally available for micro-CHP are 1–9 kWe, with overall efficiencies in excess of 90%. Emissions from current Stirling burners can be ten times lower than that emitted from gas Otto engines with catalytic converter, making the emissions generated from Stirling engines comparable with those from modern gas burner technology. Stirling engines, being external combustion machines, have a number of advantages in terms of reliability and performance and ultimately should have a cost between that of spark and compression ignition automotive units, although current capital costs are high. Service intervals of be-

Table 8.4 Stirling engine manufacturers [8]

Manufacturer/location	
DTE Energy Technologies Kockums AB Sweden	55 kW–1 MW, overall efficiency of 84%
Sigma Elektroteknisk AS, Norway	3 kW_e electrical output, 9 kW thermal output, Electrical efficiency > 25%
SOLO Kleinmoteren GmbH, Germany	2–9 kW electrical output, 8–24 kW thermal output, overall efficiency 92–96%
Stirling Energy Systems, Phoenix, AZ, USA	
Stirling Technology Co., Kennewick, WA, USA	
Stirling Technology, Inc., Athens, OH, USA	
Sunpower, Athens, OH, USA	7 kW electrical output
Tamin Enterprises, Half Moon Bay, CA, USA	
Whisper Tech Limited, New Zealand	Up to 1 kW electrical output, 7.5–12 kW thermal output

tween 3,500 h and 5,000 h (equivalent to more than 1 year's economic operation) are expected compared with 750–1000 h for IC engines. (Claims of longer service intervals are normally based upon oversized components such as large oil reservoirs which cannot be applied in normal domestic systems.) Life expectancy should be 50–60,000 h compared with 10,000 h for an IC engine. Table 8.4 presents some of the Stirling engine manufacturers (some in the development stage).

8.2.3 Fuel Cells for Micro-CHP

A fuel cell is an electrochemical device for the direct conversion of the chemical energy of hydrogen into electricity, heat and water vapor. This conversion can be done with very high electrical efficiency (35–55%) and with minimum environmental intrusion. These two aspects have rendered fuel cells the most likely energy conversion devices in the medium to long term, in both transport and stationary applications and for all power ranges. The capability of fuel cells to operate with a variety of fuels is of particular interest to the present study, since this makes them a favorite candidate for the optimal use of biofuels.

The basic operation of a fuel cell is exactly the opposite of electrolysis. In an electrolyzer, an electric current is passed through water which is broken into oxygen and hydrogen. In a fuel cell hydrogen and oxygen are combined producing an electric current and water. The principle was demonstrated by Sir W. Grove in 1839. Fuel cells operate very much like batteries, the main difference being that in batteries the reactants are stored within the battery itself and are limited by its size, while in a fuel cell they are stored externally and energy can be produced as long as fuel is fed to the anode and an oxidant to the cathode. The most common types of fuel cells are:

- Proton exchange membrane fuel cells (PEM) where the electrolyte is an ion exchange membrane. PEM fuel cells have the potential for the low costs that would make them suitable for home, farm, and similar small applications. A particular example is the direct methanol fuel cell (DMFC).
- Alkaline fuel cells (AFC), where the electrolyte is an 80% concentrated solution of KOH. They were the first in the market in spacecraft applications and have thermal efficiencies of up to 70%, but are typically too expensive for commercial use.
- Phosphoric acid fuel cells (PAFC) where the electrolyte is 100% concentrated phosphoric acid. They are already commercially viable for some applications and can approach thermal efficiencies of 85% if the steam byproduct is applied rather than wasted.
- Molten carbonate fuel cells (MCFC) where the electrolyte is alkali carbonates that in the high operating temperatures of this fuel cell (1,200°F) form molten salts. They are probably limited to industrial applications.
- Solid oxide fuel cells (SOFC) where the electrolyte is a solid, non-porous metal oxide. SOFC operate around 1,800°F and are thus probably limited to industrial applications and large power plants.

Fuel cells are expensive to build since demand has not reached the level that would allow mass production, meaning many devices are still built by hand. Additionally, some fuel cells use expensive materials, such as platinum. The average cost of fuel cells (depending on type and technology) for micro-CHPapplications is 5,000–15,000 €/kW.

Even though reliability is potentially higher than that of competing technologies, currently the reliability of fuel cells and their operating life is lower, due to the immaturity of the technology. Guarantees offered by most fuel cell manufacturers are limited to 1 year or 1,500 operating hours; therefore long term O&M costs are a significant cost factor [8].

The cost of integration of fuel cells into an existing micro-CHP energy system is considerable compared to other conventional solutions. In most cases the fuel that will drive fuel cells (pure hydrogen, biogas, other hydrocarbons) is not available on site and should also be purified so as not to poison the fuel cell catalyst. Therefore a drying and purification unit should be integrated into the energy system and this naturally increases the overall cost. In the case where fuel cells are driven by pure hydrogen, an electrolyzer with a considerable cost should also be added. These costs are eliminated when fuel cells driven by available on-site natural gas are used. Moreover, most fuel cells with a small to medium capacity, suitable for integration in micro-CHP energy systems deliver DC current, and therefore a DC/AC inverter and other power electronics with a considerable capital cost should also be added. In addition, safety precautions that should be taken into consideration in the presence of hydrogen also increase the cost of integration of fuel cells into an existing micro-CHP energy system.

Fuel cell systems do not involve the combustion processes associated with reciprocating internal combustion engines and micro-turbines. Consequently, they

Table 8.5 Estimated fuel cell emission characteristics [3, 9]

Fuel cell type	PEMFC	PEMFC	PAFC	SOFC	MCFC
Nominal electrical capacity (kW_{el})	10	200	200	100	250
Electrical efficiency (%) HHV	30	35	36	45	46
Emissions					
NO_x (ppmv at15% O_2)	1.8	1.8	1.0	2.0	2.0
CO (ppmv at 15% O_2)	2.8	2.8	2.0	2.0	2.0
Unburnt hydrocarbons (ppmv at 15% O_2)	0.4	0.4	0.7	1.0	0.5
CO_2 (lb/MW h)	1360	1170	1135	910	950
Carbon (lb/MW h)	370	315	310	245	260

have the potential to produce fewer emissions. The major source of emissions is the fuel processing subsystem because the heat required for the reforming process is derived from the anode-off gas that consists of about 8–15% hydrogen, combusted in a catalytic or surface burner element. The temperature of this lean combustion process, if maintained below 1000°C, prevents the formation of oxides of nitrogen (NO_x). In addition, the temperature is sufficiently high for the oxidation of carbon monoxide (CO) and unburnt hydrocarbons. An absorbed bed helps in removing other pollutants such as oxides of sulfur (SO_x) (see Table 8.5).

8.2.4 Biofuels for Micro-CHP

Biomass can be used as a fuel for micro-CHP installations after pre-treatment and conversion into an applicable fuel. The conversion of the raw biomass into an applicable fuel can take place coupled with the final application at one location, or uncoupled with conversion and application at different locations. Uncoupled conversion has the advantage that large scale biomass pre-treatment and conversion technologies can be used; a disadvantage is the need for a distribution system for the final product, although it must be recognized that in coupled systems biomass transportation to the site also often takes place. Table 8.6 provides an overview of possible biomass-to-application chains for coupled supply chains that could be suitable for the current study [10].

Table 8.6 Coupled biomass-to-application chains suitable for micro-CHP

Biomass product category	Conversion technology	Product	Application
Solid biomass	Combustion	Hot flue gas	Stirling engine
	Gasification	Producer gas	Micro-turbine, Fuel cell
Liquid biomass	–	–	Micro-turbine
Gaseous biomass	Anaerobic digestion (manure)	Biogas	Micro-turbine

Examples of coupled biomass-to-application chains are the conversion of solid biomass, *i.e.*, wood chips, pellets, or briquettes into heat and application in a Stirling engine. For use in a Stirling engine a clean gaseous heat flow of a temperature of more than 900°C is needed. Anaerobic digestion of manure is a common CHP application, usually in the range of 35–300 kWe, so it can be regarded either as micro-CHP or small scale CHP. Anaerobic digestion of sludge and landfill gas extraction and electricity are usually performed at capacity levels substantially higher than 50 kWe. Liquid biomass like biodiesel, bio-ethanol, pure vegetable oil, and pyrolysis oil are all the result of conversion and upgrading of the biomass at a central facility site.

8.3 Market Survey on Future Penetration of Biofuel Micro-CHP in Europe

A market survey on the possible future penetration of the three biofuel micro-CHP technologies under examination, namely micro-turbines, Stirling engines, and fuel cells has been carried out for 25 European countries (EU-25): Belgium, Czech Republic, Denmark, Germany, Estonia, Greece, Spain, France, Ireland, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Slovenia, Slovakia, Finland, Sweden, and United Kingdom. Table 8.7 summarizes the basic technological and economic parameters that have been used for the assessment of the market potential of the three technologies. The unit sizes, electric, and thermal efficiencies are based on the available data on the state of the art micro-CHP technologies that have been presented in the previous sections, while unit prices include the overall cost for the micro-CHP system together with the costs pertaining to the fuel system, *e.g.*, fuel drying and purification unit for a fuel cell, *etc.* The assumed prices, especially for the Stirling engine and fuel cell units, also reflect the fact that the engines will become cheaper as the market size increases, but they are both considerably higher than the micro-turbine unit price.

Due to lack of detailed data concerning the actual number of boilers in the countries under survey that could be replaced by micro-CHP units, the study is based upon the calculation of a number of "typical" boilers in each country and the corresponding full-load hours of operation per year. In order to evaluate these figures, the study has been based on available data from Eurostat concerning the

Table 8.7 Basic technological and economic assumptions for the three technologies

Unit type	Unit size (kW_{el})	Electric efficiency (%)	Thermal efficiency (%)	Unit price (Euro/kW)	Maintenance costs (Euros/kWh)
Micro-turbine	18.0	25.0	60.0	1,000	0.01
Stirling engine	2.0	20.0	60.0	1,800	0.02
Fuel cell	6.0	40.0	50.0	3,000	0.02

yearly fuel consumption and electricity consumption for households, coupled with available data on total population per country, average number of persons per household, and building distributions. The Eurostat final energy consumption data from households that have been used for the calculations are presented in Table 8.7. Based on the population of each country, the household fuel energy consumption and electricity consumption per capita is calculated. Eurostat provides the household energy consumption per capita, which also includes electricity consumption for heating and other appliances. By subtracting the fuel energy consumption from the Eurostat energy consumption, the electricity consumption per capita for space heating/water heating is obtained. Next, the total efficiency for household fuel consumption is calculated per country for the fuel mixture used (electricity for space/water heating included), by assuming a fuel efficiency of 70% for gas + petroleum, 40% for solid fuels, 20% for biomass, and 95% for electricity. The above-mentioned calculations are presented in Tables 8.8 and 8.9.

Available data on the average number of persons per household and percentage distribution of buildings per category (detached and semi-detached single family house, building with less than 10 dwellings, building with more than 10 dwellings), have been used to calculate the number of buildings per category and persons per building, with the assumption of a fixed number of families per type of building (1, 6, 18 for each type of building respectively, uniform throughout Europe since no other data are available). Data on average persons per family and distribution of buildings were available only for the EU-15. For the rest of the EU-25, persons per family have been assumed higher, due to a lower GDP, and the buildings distribution was chosen the same as in neighboring EU-15 countries. The aforementioned data are summarized in Table 8.10

The above calculated data on the energy consumption and efficiency, buildings and persons per building category (Table 8.11) are used in order to calculate a number of "typical" size boilers per building type and fuel category, the average full load hours a micro-CHP unit of a given output can be operated, based on the estimated electricity demand of the building, and the heat requirements per building. The number of boilers of a given fuel type X is given by the following formula:

$$Boilers\ of\ a\ fuel\ type\ X = \frac{efficiency\ of\ \ fuel\ X\ input\ \ fuel\ X}{average\ efficiency\ X\ total\ input\ \ fuel} \cdot total\ number\ of\ \ households$$

The efficiencies of fuel X used in the calculations are 70% for gas + petroleum, 40% for solid fuels, and 20% for biomass. The calculated numbers of boilers for the 25 countries under investigation for each building category and type of fuel is presented in Table 8.11.

The estimation of the market potential for the three types of micro-CHP units is conducted next. The units were chosen so that each unit size can cover the needs of a particular type of building: the 2-kW Stirling engine for detached and semi-detached single-family houses, the 6-kW fuel cell for buildings with less than ten dwellings and the 18-kW micro-turbine for buildings with more than ten dwellings and therefore each technology is examined in terms of possible market penetration in the particular market segment. The estimation has been based on the combina-

tion of two factors: the first one is a "marketability factor", defined by the ratio capital cost/GDP per building, the latter obtained from Eurostat. This factor has been used in order to represent the maximum capital investment relative to the income in a particular country that the residents of a building would be willing to pay for the purchase of micro-CHP equipment. The second is the payback factor, representing the economic usefulness of the capital investment. For each of the two factors, a maximum acceptable value is set rendering the factor 0, while for values less than the maximum, there is a linear variation of the factor from 0 to 1. For the present study, the maximum values of the factors have been set to 10% of the GDP (per building) and 7 years for the payback period.

The payback period is calculated from the capital costs and the annual profit from the investment in each case. The annual profit equals to the annual costs for operation of the units (CHP fuel + maintenance) minus the cost of displaced fuel and cost of electricity displaced. The cost of displaced fuel is calculated by the following equation:

$$\text{Heat output (CHP)} \times \text{Price of fuel displaced/Thermal efficiency of fuel displaced,}$$

where

$$\text{Heat output (CHP)} = \text{Full load hours} \times \text{Unit size} \times \text{Thermal efficiency/Elec. efficiency}$$

The calculation of the annual profit includes an adjustment if the heat coverage of the micro CHP system is greater or equal to 100%, to account for the actual heat requirement of the building. If it is greater than unity, only 100% of the heat requirement is included in the profit calculation, assuming that the rest is not used. For the above calculations, the operating and economic data of the units (Table 8.7), the estimated full load hours of operation of the units, and the prices of electricity and fuels (cogeneration fuel and fuel displaced) have been used.

As concerns the electricity price and fuel prices, data were acquired from the Eurostat database for the various European countries. The electricity prices were found in the form of yearly prices per kWh including taxes for different ranges of electricity consumption. The biomass price has been assumed equal to 0.01 Euros/kWh_{th}. Table 8.12 presents basic input data for the above describe calculations, while Table 8.13 presents the results of the survey for the possible future penetration of the selected biofuel micro-CHP systems.

The results show a potential of ca. 6 million units of 2-kW Stirling engines for detached and semi-detached single-family houses, 180,000 units for 6-kW fuel cells for buildings with less than 10 dwellings, and 1.2 million units of 18-kW micro-turbine units for buildings with more than 10 dwellings for the EU-25, with an annual electricity fed to the grid of ca. 122 TWh. The results also include an estimation of the required annual biomass quantities for operation of the installed units, for typical biomass, for each country under investigation. The availability of the quantities is an additional another factor that could affect the market potential. Nevertheless, the current survey shows that there is indeed a significant potential in Europe for application of decentralized micro-CHP technologies in the future.

Table 8.8 Final energy consumption from households for various fuels and electricity (source: Eurostat)

Country	Solid fuel (kTOE – kilo Tons of Oil Equivalent)	Hard coal (ktons)	Coke (ktons)	Patent fuel (ktons)	Lignite and peat (ktons)	Brown coal briquettes (ktons)	Petroleum products (kTOE)	Natural Gas (kTOE)	Renewables (wood, wood waste, *etc.*) (kTOE)	District heating (TJ)	Electricity (GWh)
Belgium	225	304	7	7	0	5	4,304	3,457	152	15	25,921
Czech Republic	861	1,816	157	0	6	123	6	2,230	52	1,282	14,121
Denmark	20	33	0	0	0	1	1,338	659	551	1,502	10,181
Germany	1,203	440	212	105	25	1,484	27,408	24,725	4,048	0	131,172
Estonia	35	39	0	0	4	18	129	37	328	393	1,584
Greece	25	2	0	0	0	64	3,756	9	704	28	15,775
Spain	67	120	0	0	0	0	5,039	2,513	2,063	0	50,636
France	545	668	39	139	1	0	14,249	8,407	7,278	0	132,998
Ireland	447	288	0	46	622	261	1,068	475	47	0	7,449
Italy	16	1	23	0	0	0	6,770	14,167	1,426	0	62,957
Cyprus	0	0	0	0	0	0	85	0	45	0	1,157
Latvia	55	81	0	0	0	0	91	79	848	465	1,317
Lithuania	81	120	0	0	14	11	38	112	509	552	1,811
Luxembourg	4	0	0	0	0	8	295	228	15	16	737
Hungary	276	387	9	0	215	61	293	3,282	345	607	10,440
Malta	0	0	0	0	0	0	18	0	0	0	500
Netherlands	33	32	0	0	23	0	646	7,826	155	158	22,800
Austria	223	92	178	1	45	65	2,179	1,458	2,070	508	15,685
Poland	6,330	10,184	685	0	330	1	3,935	3,036	3,104	4,968	21,659
Portugal	0	0	0	0	0	0	789	147	1,150	7	11,382
Slovenia	2	3	0	0	2	0	654	65	361	97	2,704
Slovakia	397	88	0	0	11,02	1	84	1,603	3	782	4,907
Finland	25	4	0	0	94	0	1,732	26	1,182	1,433	19,940
Sweden	0	0	0	0	0	0	1,350	44	877	2,404	41,416
UK	1,511	1,868	178	391	0	0	1,614	29,128	357	12	11,4534

Table 8.9 Calculations of household energy consumption and efficiency

Country	Population (thousands)	Calculated household fuel energy consumption per capita (kgOE)	Household energy consumption per capita (kgOE) – from Eurostat tables	Calculated household electricity consumption per capita (kWh)	Calculated household electricity consumption for heating per capita (kWh)	Total input fuel (kTOE)	Calculated total efficiency for household fuel consumption (%)
Belgium	10,333	788	898	2,509	1,284	9,279	71.5
Czech Republic	10,205	312	524	1384	2,471	5,347	74.9
Denmark	5,411	481	785	1,882	3,534	4,248	73.2
Germany	82,489	696	732	1,590	423	60,382	67.3
Estonia	1,359	396	702	1,166	3,558	954	62.8
Greece	11,003	408	445	1,434	425	4,896	64.7
Spain	41,201	235	311	1,229	884	12,814	67.9
France	59,486	512	632	2,236	1,391	37,595	64.6
Ireland	3,932	518	667	1,894	1,733	2,623	69.6
Italy	57,157	392	478	1,101	1,006	27,321	71.9
Cyprus	710	183	328	1,630	1,685	233	71.4
Latvia	2,339	463	611	563	1,717	1,429	45.4
Lithuania	3,436	219	400	527	2,104	1,374	61.2
Luxembourg	446	1,216	1,383	1,652	1,942	617	71.6
Hungary	10,159	414	548	1,028	1,553	5,567	71.6
Malta	396	45	156	1,263	1,286	62	87.7
Netherlands	16,149	537	628	1,412	1,064	10,142	72.8
Austria	8,053	738	875	1,948	1,594	7,046	58.3
Poland	38,174	433	471	567	444	17,980	53.0
Portugal	10,368	201	301	1,098	1,161	3,121	59.9
Slovenia	1,995	543	594	1,355	588	1,185	56.9
Slovakia	5,379	392	549	912	1,831	2,953	73.2
Finland	5,201	577	997	3,834	4,888	5,185	69.1
Sweden	8,925	261	854	4,640	6,898	7,622	81.8
UK	59,234	551	744	1,934	2,250	44,070	75.1

Table 8.10 Data and calculations of buildings/persons

	Available data/assumptions				Buildings per category			Persons per category		
Country	Average persons per household	Detached and semi-detached single family house (%)	Building with less than 10 dwellings (%)	Building with more than 10 dwellings (%)	Detached and semi-detached single family houses	Buildings with less than 10 dwellings	Buildings with more than 10 dwellings	Persons per Detached and semi-detached single family house	Persons per Building with less than 10 dwellings	Persons per Building with more than 10 dwellings
Belgium	2.4	77.9	11.3	10.8	3,355,692	80,902	25,795	2.40	14.40	43.20
Czech Republic	3.0	55.4	2.9	41.7	1,884,257	16,675	78,742	3.00	18.00	54.00
Denmark	2.2	57.4	14.2	28.4	1,430,123	59,079	39,386	2.17	13.02	39.06
Germany	2.2	39.2	38.2	22.5	14,703,922	2,389,387	469,709	2.20	13.20	39.60
Estonia	3.0	55.4	2.9	41.7	25,0926	2,221	10,486	3.00	18.00	54.00
Greece	2.6	45.6	32.8	21.6	1,929,259	231,649	50,709	2.60	15.60	46.80
Spain	3.0	36.8	17.2	46.1	5,049,142	392,711	351,570	3.00	18.00	54.00
France	2.4	57.4	14.2	28.4	14,215,404	587,246	391,497	2.40	14.40	43.20
Ireland	3.0	93.1	3.9	2.9	1,220,719	8,566	2,142	3.00	18.00	54.00
Italy	2.6	31.9	35.8	32.4	7,004,534	1,311,105	395,128	2.60	15.60	46.80
Cyprus	3.0	45.6	32.8	21.6	107,892	12,955	2,836	3.00	18.00	54.00
Latvia	3.0	55.4	2.9	41.7	431,874	3,822	18,048	3.00	18.00	54.00
Lithuania	2.7	33.1	4.8	62.1	421,228	10,181	43,904	2.70	16.20	48.60
Luxembourg	2.5	66.7	20.1	13.2	118,933	5,976	1,312	2.50	15.00	45.00
Hungary	3.0	45.6	32.8	21.6	1,543,770	185,363	40,577	3.00	18.00	54.00
Malta	3.0	45.6	32.8	21.6	60,176	7,225	1,582	3.00	18.00	54.00
Netherlands	2.3	67.2	5.4	27.5	4,715,288	63,100	107,079	2.30	13.80	41.40
Austria	2.4	43.6	15.2	41.2	1,463,883	84,982	76,758	2.40	14.40	43.20
Poland	3.1	55.4	2.9	41.7	6,887,753	60,954	287,836	3.07	18.42	55.26
Portugal	2.9	68.1	20.1	11.8	2,436,024	119,757	23,367	2.90	17.40	52.20
Slovenia	3.0	43.6	15.2	41.2	290,123	16,842	15,212	3.00	18.00	54.00
Slovakia	3.0	43.6	15.2	41.2	782,240	45,411	41,016	3.00	18.00	54.00
Finland	2.1	55.4	2.9	41.7	1,371,879	12,141	57,330	2.10	12.60	37.80
Sweden	1.9	55.4	2.9	41.7	2,601,974	23,026	108,735	1.90	11.40	34.20
UK	2.4	81.9	11.3	6.9	20,204,408	463,774	94,099	2.40	14.40	43.20

Table 8.11 Calculated number of "typical size" boilers per building category

Country	Boilers with solid fuels			Boilers with petroleum products and natural gas			Boilers with renewables (wood, wood waste, *etc.*)		
	Detached and semi-detached single family house	Building with less than ten dwellings	Building with more than ten dwellings	Detached and semi-detached single family house	Building with less than ten dwellings	Building with more than ten dwellings	Detached and semi-detached single family house	Building with less than ten dwellings	Building with more than ten dwellings
Belgium	45,504	1,097	350	2,746,809	66,223	21,115	15,370	371	1,182
Czech Republic	161,952	1,433	6,768	736,020	6,513	30,758	4,891	43	2,044
Denmark	3,679	152	101	642,682	26,550	17,700	50,674	2,093	13,956
Germany	174,137	28,297	5,563	13,206,151	2,146,000	421,863	292,979	47,609	93,590
Estonia	5,863	52	245	48,623	430	2,032	27,474	243	11,481
Greece	6,089	731	160	1,604,485	192,653	42,173	85,729	10,294	22,533
Spain	15,552	1,210	1,083	3,067,627	238,593	213,598	239,435	18,623	166,718
France	127,566	5,270	3,513	9,280,435	383,380	255,587	851,765	35,187	234,579
Ireland	119,614	839	210	722,403	5,069	1,267	6,288	44	110
Italy	2,282	427	129	5,226,172	978,232	294,810	101,702	19,037	57,371
Cyprus	0	0	0	38,617	4,637	1,015	5,841	701	1,535
Latvia	14,652	130	612	79,101	700	3,306	112,955	1,000	47,204
Lithuania	16,222	392	1,691	52,409	1,267	5,463	50,968	1,232	53,124
Luxembourg	431	22	5	98,550	4,952	1,087	808	41	89
Hungary	42,783	5,137	1,125	969,888	116,456	25,493	26,739	3,211	7,028
Malta	0	0	0	13,993	1,680	368	0	0	0
Netherlands	8,432	113	191	3,788,244	50,694	86,027	19,802	265	4,497
Austria	31,779	1,845	1,666	907,136	52,661	47,565	147,495	8,562	77,338
Poland	1,831,381	16,207	76,533	3,529,499	31,235	147,496	449,021	3,974	187,644
Portugal	0	0	0	853,865	41,977	8,191	299,885	14,743	28,766
Slovenia	344	20	18	216,557	12,572	11,355	31,073	1,804	16,293
Slovakia	57,456	3,335	3,013	427,381	24,811	22,409	217	13	114
Finland	3,827	34	160	470,971	4,168	19,682	90,472	801	37,808
Sweden	0	0	0	407,316	3,605	17,022	73,235	648	30,604
UK	369,126	8,473	1,719	13,142,433	301,673	61,209	43,606	1,001	2,031

Table 8.12 Basic economic input for the calculations

Country	GDP (MEuros)	GDP per capita (Euros)	Electricity price (Euro/kWh) (Eurostat)	N.G. fuel price (Euros/kWh) (Eurostat)
Belgium	245,343	23,744	0.0926	0.0319
Czech Republic	44,450	4,356	0.0491	0.0227
Denmark	161,384	29,825	0.2075	0.0453
Germany	2,076,860	25,177	0.1008	0.0366
Estonia	4,000	2,943	0.0615	0.0141
Greece	115,046	10,456	0.0579	0.0450
Spain	566,378	13,747	0.0707	0.0369
France	1,400,756	23,548	0.0930	0.0324
Ireland	92,225	23,455	0.0777	0.0317
Italy	942,346	16,487	0.1834	0.0450
Cyprus	8,656	12,192	0.0708	0.0450
Latvia	5,166	2,209	0.0463	0.0139
Lithuania	18,084	5,263	0.0647	0.0165
Luxembourg	20,051	44,957	0.0852	0.0276
Hungary	44,641	4,394	0.0809	0.0194
Malta	3,117	7,871	0.0958	0.0450
Netherlands	386,785	23,951	0.1222	0.0347
Austria	209,993	26,076	0.1125	0.0321
Poland	222,486	5,828	0.0535	0.0223
Portugal	101,933	9,832	0.0874	0.0423
Slovenia	20,062	10,056	0.0723	0.0282
Slovakia	19,256	3,580	0.0772	0.0246
Finland	129,171	24,836	0.0683	0.0266
Sweden	229,349	25,697	0.1170	0.0422
UK	1,051,071	17,744	0.0647	0.0233

Table 8.13 Basic results on market penetration of selected biofuel micro-CHP technologies

Country	2-kW Stirling		6-kW fuel cell		18-kW micro-turbine		Annual biomass consumption (ktonnes) LHV = 8 MJ/kgr – 30% moisture
	No. of Units	Electricity generation (GWh)	No. of Units	Electricity generation (GWh)	No. of Units	Electricity generation (GWh)	
Belgium	602,506	3,627	10,326	373	15,426	1,672	11,590
Czech Republic	0	0	0	0	5,171	386	696
Denmark	192,791	787	8,752	214	19,912	1,463	4,646
Germany	1,915,663	6,702	3,629	76	302,099	19,023	49,407
Estonia	0	0	0	0	0	0	0
Greece	0	0	0	0	20,447	1,372	2,470
Spain	34,821	128	58	1	151,583	10,060	18,398
France	1,455,850	7,812	49,880	1,606	268,662	25,949	66,092
Ireland	216,919	1,233	663	23	1,099	112	3,002
Italy	351,611	1,007	94,269	1,620	200,758	10,349	22,716
Cyprus	364	2	146	4	833	73	141
Latvia	0	0	0	0	0	0	0
Lithuania	0	0	0	0	58	1	3
Luxembourg	19,369	80	3	0	781	58	285
Hungary	0	0	0	0	3,410	189	341
Malta	0	0	0	0	172	12	21
Netherlands	513,722	1,668	1,214	24	55,920	3,269	9,663
Austria	196,473	918	9,021	253	67,638	5,691	12,595
Poland	0	0	0	0	13,579	426	766
Portugal	0	0	0	0	4,010	230	414
Slovenia	0	0	0	0	5,359	392	706
Slovakia	0	0	0	0	967	48	86
Finland	94,196	758	575	28	27,444	3,977	8,897
Sweden	94,633	834	1,091	58	23,277	3,694	8,592
UK	272,304	1,264	1	0	33,084	2,764	7,818
Total	5,961,222	26,821	179,628	4,280	1,221,689	91,211	229,342

8.4 Conclusions

The current work has presented results from the European co-ordination action project MICROCHEAP that was intended to bring together industrial specialists and research experts to focus entirely on renewable micro-CHP technology, co-ordinate and steer research in this field, and highlight the most promising technologies with the highest potential for market penetration in existing and future market conditions. The state of the art in technological options in the field of renewable micro-CHP with biofuels with regards to technology, cost, and environmental impacts has been presented in detail and results of a market survey have been provided, concerning the possibility of future penetration of three selected biofuel micro-CHP technological options in Europe. The results have demonstrated a significant potential for future application of the technology in households. Further technological developments and capital investment reductions might make such installations even more feasible in the near future.

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